USE OF AIRBORNE GPS DATA FOR HIGHWAY MAPPING

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ABSTRACT

The use of airborne global positioning systems (GPS) data in aerial triangulation of parallel strip blocks results in a significant reduction in the need for ground control. In the case of strip aerial triangulation usually required for highway corridor mapping, such advantage of using GPS data has not been fully realized. In addition to the cost benefits resulting from the reduction in the ground control, the California Department of Transportation (Caltrans) has additional incentive in eliminating serious concerns about the safety of field surveyors exposed to the extreme hazards of high speed vehicular traffic.

The use of an inertial navigation system (INS) in combination with an aerial camera and a GPS receiver has been reported in order to supplement the GPS data with the camera attitude data during the flight mission. However, no systematic study to analyze the precision needed for the attitude data has been reported. Therefore, by using simulated strip data, the impact of adding the camera attitude control in addition to the airborne GPS data is investigated through a systematic and rigorous error analysis of strip aerial triangulation

The procedure used for the validation of the theoretically derived results through test flights of strip-photography flown at 1:3,000 scale is discussed and results analyzed. Based on this experience, preliminary specifications for practical implementation of the use of airborne GPS data for aerial triangulation for highway and other corridor mapping are discussed.

1 INTRODUCTION

1.1 Objective of Study

Photogrammetric mapping has traditionally required extensive ground measurements of photo identifiable points to maintain horizontal and vertical accuracy and to reference the mapping to the desired datums. With the continuing increase in the cost of field survey operations, the alternative approach for the densification of the control through aerial triangulation, results in significant cost benefits. Consequently, Caltrans routinely uses analytical aerial triangulation for controlling photogrammetric models and meets the specified 1-σ accuracy standard of 1/10,000 of the flying height above terrain. The block adjustment, however, still requires some field surveyed points appropriately distributed in the block. Targeting and surveying such points often places high demand on time and cost. In addition, according to the current practice in Caltrans, several height control points often need to be located in the median thus exposing Caltrans surveyors to the extreme hazards of high speed vehicular traffic.

It has long been a goal of the photogrammetric mapping community to eliminate, or at least reduce, this element of the mapping process by determining the spatial coordinates of the perspective center of the aerial camera at the instant of exposure of the aerial photograph. GPS technology has provided the first means of accurately and reliably positioning an aerial camera at a reasonable cost for even large-scale mapping. Realizing this potential, airborne GPS control projects were undertaken in the late 1980's and early 1990's, by various groups including the NGS (Lucas1987), the Texas Department of Transportation (Baines 1995), and others in US and by several photogrammetrists in Canada (Goldfarb 1985), Germany (Ackermann 1992) and (Friess 1992), Norway (Blankenberg 1992 and 1994), and Spain (Colomina et all 1992). These projects mainly attempted to demonstrate the potential of the technique when multi-strip blocks are to be processed.

The incorporation of GPS-derived camera position data in the bundle block adjustment offers an alternative to conventional aerial triangulation, which is not only economically attractive but eliminates, to a large extent, the safety concerns for Caltrans field survey personnel. In order to carry out a systematic and comprehensive analysis of the different aspects of the integration of GPS-determined camera station positions into the aerial triangulation adjustment procedures to meet Caltrans' photogrammetric mapping specifications, a research study was undertaken at the California State University, Fresno. This paper is based on some of the results achieved in this study.

1.2 Literature Review

A comprehensive review of the literature indicated that the major technical considerations for the use of the airborne GPS data in aerial triangulation include the geometry and layout of aerial strips, the need for auxiliary sensors (GPS and INS), the integration of airborne sensors with an aerial camera, and the approach used for the GPS data collection and processing, and for the aerial triangulation bundle adjustment. None of the studies, however, has made a comprehensive theoretical analysis, supported by practical tests, for the optimal precision of the airborne GPS data, the density and the distribution of field-surveyed control in order to achieve a clearly specified photogrammetric precision using strip photography.

More than 95 percent of the airborne GPS data controlled aerial triangulation projects reported in the literature involved aerial photo blocks. In the case of photo strips commonly used by Caltrans (and other state transportation agencies, utility companies, etc.) for corridor mapping, the airborne GPS control does not control tilt across the flight line. Consequently, the photo strip scenario provides a challenge absent in a photo block. The few cases reported, (Abdullah 1997), (Merchant 1994), (Fraser et all 1998), where airborne GPS data was used for a single photo strip, involved short strips of 6 to 10 models. It soon became clear that the use of airborne GPS data for aerial triangulation of photo strips should be thoroughly investigated.

The use of the airborne GPS data does not provide any control across the flight line, and requires that the attitude of the photo (usually represented by three rotational angles, ω, ϕ, κ) must also be established. This can be achieved through the integration of an airborne Inertial Navigation System (INS) with the aerial camera. Most of the INS units deployed are bulky and expensive, and their use has mostly been limited to small scale aerial photography. More recently, Applanix (Lithopoulos et all 1998) has developed an airborne GPS-INS blended system for obtaining the position as well as the attitude of the aerial camera. The sensor integration requires that the GPS receiver and the INS must be integrated geometrically, as well as, electronically with the aerial camera, so that the camera position and its attitude data can be collected synchronously with the operation of the camera shutter. Although the integration of the GPS hardware with the aerial camera is achieved easily and accurately, such integration of the INS with the aerial camera is more complex. Satisfactory methodology for calibrating such an integrated system is still being researched.

GPS positions are referenced to the GPS antenna mounted on the upper side of the aircraft. These positions must be transformed to the perspective center of the aerial camera. In relation to the ground coordinate system, this spatial offset varies with the rotations between the camera and the aircraft, and between the aircraft and the ground. If the camera is locked during the photo mission, it is easy to correct for this offset in the block adjustment. The requirement to lock the camera, especially to keep crab settings constant during the flight, may pose some problems in the ability to control the tilt and to uniformly maintain the specified overlap. If the GPS antenna is mounted directly above the camera as suggested by (Ackermann 1992), the crab angle will hardly affect the offset vector. Tilt corrections for the camera will still change the offset vector, although the tilt effect will be small and can usually be neglected.

Accurate relative kinematic GPS positioning is derived from simultaneous carrier phase measurements made with the airborne and the ground-based GPS receivers. The carrier phase observations measure only the phase shift within one cycle. The total integer number of cycles the signal travels through from the satellite to the receiver, usually called the initial phase ambiguity, needs to be resolved. Such initial solution for phase ambiguities remains valid while each receiver maintains continuous lock on at least five satellites. In case of loss of lock to the minimum number of satellites, due to cycle slips or signal interruptions, a fresh set of phase ambiguities are introduced and must again be resolved.

While (Baines 1995), (Curry et all 1993), (Lapine 1989), and (Lucas 1987), amongst others have proposed the approach for static resolution of the ambiguities before the aircraft takes off, such an approach imposes serious constraints on the maneuverability of the aircraft. Sometimes, to allow very wide turns and shallow banks, the flight lines were flown out of sequence as reported by (Baines 1995). Due to recent advancements in the GPS hardware resulting in 'P-Code receivers', more advanced algorithms have been developed to resolve the ambiguities on-the-fly (OTF). The OTF ambiguity resolution is increasingly being adopted as the method of choice, (Hussain et all 1999). There is a danger of cycle slips due to multi-path from the reflective aircraft surface, as well as the loss of lock to some of the satellites during banks and turns. As long as lock to satellites can be continuously maintained, the ambiguities are easily recovered.

In the aerial kinematic environment, there is always a risk that not only the initial ambiguity resolution could be inaccurate, but also it is often difficult to detect errors in the estimated ambiguities. This will create unacceptable uncertainty in using this approach since an error of even one cycle would translate into 19-cm error in antenna positioning. Photogrammetrists have successfully developed one solution to this problem through modeling such errors, by what are known as 'drift parameters', in the bundle block adjustment. When the ambiguities are incorrectly resolved, the computed aircraft antenna position will drift away from the true value, because the adjusted solution will be constrained to incorrect ambiguities. In spite of applying differencing techniques, uncertainties remain in the a-priori corrections, such as for tropospheric refraction, and due to unmodeled errors such as for satellite orbital errors, resulting in the drift errors. Practically all experimental tests on kinematic GPS positioning have shown some systematic GPS drift errors, and that the initial drift error is not constant but changes with time. Typical magnitude as estimated by (Ackermann 1992) may vary from 10 cm to 50 cm per hour. Six parameters, one constant and one time-dependent shift per coordinate (X, Y, and Z) can model the linear systematic errors. Since the GPS derived antenna positions are treated as observations in the block adjustment, it is possible to estimate these six drift parameters.

An elegant approach used for the processing of airborne GPS controlled aerial triangulation blocks is to transform the ground and the airborne GPS control data (latitude, longitude, and ellipsoidal height) into a local three dimensional Cartesian coordinate system, and complete all the computation and analysis for the block adjustment in such a local coordinate system. On successful completion, the resulting coordinate data may then be transformed from the local coordinate system to the desired mapping coordinate system. This approach is being used by some of the commercial software systems such as (Munjy et all 1985), (Friess 1992), amongst others. The primary advantage of this approach is that no correction for the earth curvature has to be applied to the image coordinates and the entire processing of the aerial triangulation block can be made free of any uncertainties in the geoidal height data, thus obviating the so-called "datum problem" (Ackermann 1992).

The calibrated focal length of the camera as normally used in the bundle solution has been determined in a laboratory environment. During flight, the large temperature difference between the airplane cabin and the outside environment may cause thermal stresses that can cause a significant change in the focal length of the aerial camera. Unlike the case of conventional aerial triangulation, such changes in the camera focal length cannot be ignored when airborne GPS control is used. The use of aerial triangulation software that has the functionality to carry out a bundle adjustment solution with self-calibration features that can compute and apply correction for change in calibrated focal length becomes highly desirable.

2 ERROR ANALYSIS

2.1 Enhanced Bundle Adjustment Algorithm

A commercial software package marketed as Interactive Simultaneous Bundle Block Adjustment (ISBBA), by Geomatics Technologies, LLC located in Fresno was used for processing aerial triangulation data in this study. ISBBA incorporates a bundle adjustment solution based on the well known collinearity model. In order to incorporate the GPS derived camera positions in the adjustment solution, the commonly used approach as reported by (Lucas 1987), (Lapine 1989) and others is to transform these coordinates to the camera perspective center, using the antenna-to-camera spatial vector and by also using the attitude angles (ω, ϕ, κ). In order to do so, an effort is made to measure the antenna-to-camera spatial vector between the antenna phase center and the estimated physical location of the camera perspective center. However, as pointed out by (Lapine 1989), this results in some uncertainty as to the exact physical location of the nodal points of the camera lens. A more elegant approach is to measure the antenna-to-camera spatial vector with reference to the photo coordinate axes as defined by the calibrated coordinates of the camera fiducial marks, with origin of the coordinate system located at the principal point of autocollimation. In this way, the antenna position can be established directly in the image coordinate system.

ISBBA incorporates the use of the airborne GPS antenna positions by adding three position constraint equations to the bundle, one equation each for the X-, Y- and Z-coordinate for each observed antenna location. These observed antenna coordinates are assigned relative weights in accordance with the standard errors resulting from the differential kinematic processing of the airborne GPS data. Similarly, for each photo for which the attitude is available through INS data, three attitude constraint equations are added to the collinearity observation equations for the bundle adjustment (one equation each for ω, ϕ, and κ rotation).

The ISBBA software also provides an option to include six additional unknown drift parameters for each strip during the bundle adjustment of any photogrammetric block. The observed airborne GPS antenna coordinates and the drift parameters are introduced in the bundle adjustment as additional observations via the following equation:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_A + \begin{bmatrix} VX \\ VY \\ VZ \end{bmatrix}_A = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_P + R^T \begin{bmatrix} dX \\ dY \\ dZ \end{bmatrix}_A + \begin{bmatrix} ax \\ ay \\ az \end{bmatrix}_k + \begin{bmatrix} bx \\ by \\ bz \end{bmatrix}_k (t - t_0)$$

In this equation:

$\left[X\,Y\,Z\right]_A^T$ is the vector of observed coordinates of the airborne antenna

$\left[VXVYVZ\right]_A^T$ is the vector of the corrections to the respective observed antenna coordinates

$\left[dX\,dY\,dZ\right]_A^T$ is the spatial vector linking the antenna with the camera perspective center

$\left[X\,Y\,Z\right]_P^T$ is the vector of the adjusted coordinates of the perspective center

$\left[axayaz\right]_k^T$ is the vector of constant shift in the antenna position in the *k*th strip at time t_0 caused by the incorrect resolution of integer ambiguities (3 drift parameters)

$\left[bxbybz\right]_k^T$ is the vector of time-dependent linear drift parameters for the *k*th strip

The enhanced functional capability of ISBBA software was used exclusively for processing all aerial triangulation blocks for this study and has significantly contributed to the analytical rigorousness of the study.

1.2 Generation of Simulated Data

Since aerial photography with actually observed airborne camera position and attitude data was not available, simulated data was used for the proposed investigation. Caltrans supplied data for a wide-angle aerial photography strip at 1:3,000 photo scale, including observed photo coordinates and ground control. The strategy adopted for this study was to carry out a systematic and comprehensive error analysis on simulated data in order to ascertain what level of reduction in the ground control for aerial triangulation may theoretically be achievable, through the use of airborne GPS and INS data. Only if the results of such a theoretical analysis appear promising, should this study proceed forward to validate the theoretically achieved results with corresponding results from actual test flights. Based on careful considerations, a 1-σ error of 0.006 mm in the observed image data, 5 cm in the ground control data, 5 cm to 20 cm in the airborne antenna position, and 10 arc-sec to 40 arc-sec in the camera attitude data was selected for analyzing the simulated data. Based on the above criteria, data was simulated for a 48 model long single strip at 1:3,000 photo scale. A conventional block adjustment was first performed using all the available ground control. The resulting rms for the control coordinates was less than 4.6 cm, and consequently, it met the normal accuracy expectation for aerial triangulation of 1 part in 10,000 of the flying height of 460 m above the average terrain level. The adjusted coordinates of all the pass points were then selected to represent "exact" ground coordinate data against which all accuracy tests were performed. For this study, the antenna was assumed to be located vertically above the aerial camera at a distance of 1.200 m above the perspective center.

1.1.21 Ground Control

Caltrans mapping projects mostly involve the mapping of a narrow corridor located in the middle of the aerial photo flight line. Caltrans uses ground control distribution aimed at maximizing the impact of the control, especially the height control, in the central corridor coverage. This results in a control distribution consisting of planimetric and height points placed in the wings of the flight line about 3 to 6 models apart, and a large number of additional vertical control points at a spacing of approximately one-half the airbase (137 m for 1:3,000 photo scale), concentrated in the middle of the flight line. This results in the location of 3 additional height control points in the middle of each model along the entire strip. To a large extent, it is this concentration of the control within the central median that has created the serious concern for the safety of the field survey crew and has provided the main incentive for this study.

With airborne GPS data, the need for the location of control in the center of the strip is fully satisfied, with two GPS derived positions falling in each model. Therefore, the need for any ground control is reduced to control points falling in the wing locations only. The optimal distribution for such ground control is when a pair of 3-D control points located across the flight line are uniformly distributed along the flight line. The critical issue would then be to investigate the farthest distance that such a pair of ground control points can be separated from the previous pair while still meeting the normal accuracy standard for aerial triangulation. The choice of a 48-model long flight line provided sufficient flexibility to test this hypothesis for the ground control spacing to vary from 6 models to 24 models.

The control supplied by Caltrans for the data set used for generating the simulated data had an estimated precision of 3 to 5 cm. Therefore, for this investigation, a 5 cm precision level in each ground coordinate was adopted. Use of higher precision in the ground control would assign much larger relative weight to the ground control in relation to the airborne GPS control.

2.3 Processing of Simulated Data

Several blocks were processed using simulated data to insure that the perturbations introduced in the simulated image coordinate data, airborne GPS antenna position data, and the camera attitude data displayed random behavior and did not show any systematic trends. This was necessary to ensure the validity of the procedure used for generating the simulated data for this study, which objective was fully satisfied.

2.3.1 Error Analysis with Camera Position Constraint Only

This error analysis was based on the processing of 18 different blocks and the results are summarized in Table 1. It is seen that aerial triangulation results based on a combination of 5 cm error in ground control, 10 cm error in antenna location, and a pair of wing control points spaced 6 airbases apart, would fall slightly short of meeting Caltrans accuracy standard.

Control Spacing (Airbases)	Antenna Error (cm)	RMS of X (m)	RMS of Y (m)	RMS of z (m)
6	10	0.025	0.026	0.051
6	15	0.028	0.028	0.058
9	10	0.027	0.03	0.064
9	15	0.031	0.035	0.073
12	10	0.028	0.035	0.066
12	15	0.033	0.038	0.078
15	10	0.028	0.04	0.068
15	15	0.032	0.044	0.081
24	10	0.028	0.043	0.068
24	15	0.032	0.045	0.082

Table 1: Point Positional Error with Varying Ground Control Spacing: 1:3,000 Photo Scale, Airborne GPS Control

2.3.2 Error Analysis with Camera Position and Attitude Constraint

The same 48-model long single strip data was then processed by adding the camera attitude data. Each of the 18 cases described under Section 2.3.1 required processing of 4 blocks, thus resulting in the processing of a total of 72 blocks for this case.

3 CONCLUSIONS BASED ON SIMULATED DATA RESULTS

The results of processing the simulated data blocks confirmed that the addition of camera position and attitude data to the aerial triangulation adjustment solution results in a reduction in the requirement for the number and the distribution of ground control points. For the GPS only case, the results summarized in Table 1 show that normal aerial triangulation accuracy standard would be achievable with a combination of 10 cm precision in the airborne antenna positions when used with a pair of wing control points spaced about 5 to 6 models apart along a single strip. This represents not only a reduction in the number of control points, but a far more significant advantage results from their distribution along the strip. The need for ground surveys for locating points in the median of the highway, as currently practiced at Caltrans, is completely eliminated. The required ground control is located across the flight lines away from the traveled way without subjecting the survey crews to the hazards of high-speed traffic. The central corridor of the flight line is fully controlled through the airborne GPS data. It was also tested that the enhancement in the precision of the airborne GPS data to 5 cm level still required that the ground control be spaced no more than 6 models apart.

For obvious reasons, the availability of the airborne GPS data alone, however precisely established, is not sufficient to control a single strip in the absence of any ground control. However, it was noticed that the conventional aerial triangulation accuracy can be achieved with no ground control if the airborne GPS antenna position data of up to 10 cm precision can be supplemented with INS data that establishes the camera attitude angles (ω, ϕ, κ) with a standard error below 20 arc-sec. Similar accuracy may also result if aerial triangulation data of 15-cm precision in airborne GPS positions is combined with a 10 arc-sec precision INS data. The accuracy standard is also achieved when antenna positions with 10 cm errors are combined with INS data of 40 arc-sec precision and ground control is spaced 6 airbases apart. Similar accuracy results from a combination of 10-cm error in antenna position, 20 arc-sec error in attitude data and control spacing of 12 airbases.

The GPS hardware and software technology to establish airborne antenna positions with standard error below 10 cm is available and has been proven. However, uncertainty surrounds the level of angular precision that is achievable with the INS systems that are commercially available, and are not too exorbitantly priced. A comparison of the achievable accuracy between the GPS only case and the GPS + INS case clearly shows that the dominant role is that of the availability and the spacing of the ground control points. It is significant to find that supplementing the GPS data with INS data does not offer any substantial advantage when ground control is available. Therefore the capital investment and the complexity of calibrating a GPS +INS integrated system may have to be weighed carefully, when the alternative of providing a few sparsely located ground control points can achieve the same objective.

Based on the above, it was decided that the results and conclusions drawn from theoretical error analysis of simulated data, should be validated through test flights.

4 TEST FLIGHT

4.1 Flight Planning

In order to validate the results obtained from the processing of simulated data, It was planned to collect data from 1:3,000 scale, wide-angle aerial photography, along a sufficiently long and straight flight line. This requirement was easily met by the choice of a gently undulating segment of terrain, 36 models long, centered over Interstate 5 near San Diego, California. Caltrans' District Surveys Office in San Diego established the ground control for this study. A total of 83 control points were monumented, targeted, and surveyed using static and fast-static GPS measurement method, and tied to California High Precision Geodetic Network (HPGN). Several control points were also tied to benchmarks through differential leveling. The planimetric position and the ellipsoidal heights were estimated to have a precision of 2 cm.

4.2 Flight Mission

I. K. Curtis Aerial Photographers of Burbank, California acquired the photography under their existing Caltrans contract, using a LEICA RC-20 wide-angle aerial camera mounted in a Cessna 310 aircraft. The mission was accomplished in bright and calm weather near local noon. An Ashtech Z-12 receiver was used to collect the airborne GPS data at 1-sec data collection interval, while a similar GPS receiver occupied a HPGN station located in the airport premises, near the northern end of the project site. A second Ashtech GPS receiver was located at another HPGN station near the southern end of the project, and simultaneously collected data.

4.3 Data Acquisition

The pass point selection, point transfer and the observation of the image coordinate data was completed by the staff of the Photogrammetry Branch of the Caltrans Engineering Service Center in Sacramento, California. The observations were carried out using Leica BC3 analytical plotters for this study, although future test will include the use of digital workstations (Leica DPWs).

The differential processing of the airborne GPS data was carried out at the university using Ashtech's PNAV post-processing software with respect to each base station. Both the backward and the froward solutions were obtained. No significant data interruptions during flight mission were identified.

4.4 Data Processing

The processing of the aerial triangulation blocks was carried out at the university using ISBBA software. First a conventional block was processed using all the 83 (horizontal and vertical) ground surveyed control points. The results showed complete consistency in the control data, and the residuals at the control were of the order of less than 1-cm.

Aerial Triangulation of the strip was then carried out by including the airborne GPS data with drift parameters and selecting a pair of ground control points located in the wings at a spacing of 6 airbases, and 12 airbases. This resulted in the use of 14, and 8 ground control points, respectively, for the two cases analyzed.

5 RESULTS AND DISCUSSION

The results obtained from the airborne GPS data supported aerial triangulation blocks with two different ground control configuration lend to a meaningful accuracy analysis. A large number of ground surveyed points are not used to control the block adjustment and are used as "check points". A comparison between their x-, y- and z-coordinates computed through the block adjustment was made with their known ground surveyed coordinates, and the statistics for the discrepancies between the coordinates provide a very reliable measure of the accuracy of the aerial triangulation results. Such statistics for the case of 6-airbases and for 12-airbases are summarized in Table-2. It is to be noted that there are 69 checkpoints for the 6-airbases case and 75 checkpoints for the 12-airbases spaced control block. These check points are uniformly distributed along the entire flight.

Errors (m)			
		6 Airbases	**12 Airbases**
X (Across Flight Line)	**Avg.**	-0.009	-0.018
	Abs. Avg.	0.016	0.036
	St. Dev	0.019	0.040
	Max (+) Err.	0.028	0.090
	Max (-) Err.	-0.047	-0.094
Y (Along Flight Lline)	**Avg.**	-0.005	-0.009
	Abs. Avg.	0.016	0.019
	St. Dev	0.020	0.022
	Max (+) Err.	0.039	0.036
	Max (-) Err.	-0.061	-0.055
Z	**Avg.**	0.005	0.000
	Abs. Avg.	0.022	0.029
	St. Dev	0.028	0.036
	Max (+) Err.	0.073	0.084
	Max (-) Err.	-0.071	-0.066

Table 2

Clearly, the control spacing of 6 airbases and 12 airbases easily meet the Caltrans accuracy standard of 1 part in 10,000 of the flying height above the terrain. The results are given with reference to a local three-dimensional Cartesian coordinate system, in which the y-axis is oriented across the flight line. As expected for the case of a single strip, the airborne GPS control is not effective in controlling tilt across the flight line, and therefore, the largest discrepancy of 0.036 m occurs in the y-coordinate. The distribution of the checkpoints along the flight line for the 12-airbases block is shown in Figure 1 with their height errors. The error distribution appears to be fairly random along the flight line.

It is also significant to note that the average discrepancy in the x-, y- and z-coordinate varies between 5 and 9 mm, indicating that there is no likelihood of any residual systematic errors in the block. The largest discrepancies, positive and negative, also fall within an acceptable range. The results clearly and convincingly demonstrate that the use of airborne GPS data in aerial triangulation is very effective in reducing the need for ground surveyed control points. From the point of view of highway agencies, it is also very significant that the ground-surveyed control can be located only in the wings of the flight line, away from the center of highways.

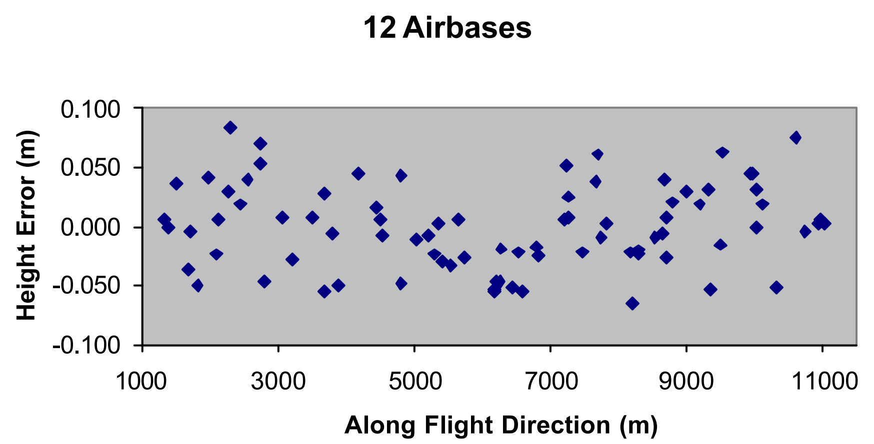

Figure 1

The aerial triangulation results of the test flight data are significantly better than those derived from the theoretical error analysis made on the simulated data. Even the test flight results from the block with control spaced 12 airbases apart are more accurate than the simulated data block with control spacing of 6 airbases. This increase in the accuracy is attributed to the superior quality of the test flight ground control data (2 cm versus 5 cm for simulated data block), and possibly also due to superior airborne GPS data (3 to 5 cm versus 10 cm for the simulated data block). In order to further probe this matter, a conventional aerial triangulation block (without airborne GPS data) was processed with ground control spacing of 12 airbases. The height errors jumped to several decimeters. This shows that even though the airborne GPS control is located in the center of a single strip, it effectively constrains the height of the exposure stations in the bundle solution.

Based on the results of the test data flight, a pair of wing control points spaced 12 airbases apart will meet Caltrans' accuracy standard for aerial triangulation of 1:3,000 scale airborne GPS controlled wide-angle photography. These results have led to an on-going re-evaluation of the precision assumptions made in the initial data simulations. Further field trials will be required to determine if the surprising results of this test are dependably repeatable. In the future, it is also planned to investigate if further reduction in the need for ground surveyed control can be achieved by using the alternate strategy of two airborne GPS controlled overlapping strips with 30 percent or 65 percent overlap.

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